DISTRIBUTION AND ENVIRONMENTAL RELATIONSHIPS OF PERMAFROST

BY

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Introductory Session

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Abstract

This general paper defines permafrost, and examines its extent, thickness and other characteristics such as ground ice and temperature regime. It deals with the effects of climatic and terrain factors on permafrost, including relief, vegetation, hydrology, and snow cover. Special problems in permafrost regions, and past and present investigations, are reviewed.

Résumé

Dans le présent document général, on donne la définition du pergélisol et étudie son étendue, son épaisseur et d'autres caractéristiques comme la glace de fond et le régime des températures. On traite également des effets des facteurs du climat et du sol sur le pergélisol, y compris le relief, la végétation, l'eau et la couche de neige. On y examine certains problèmes propres aux régions de pergélisol et traite d'études antérieures et actuelles

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DISTRIBUTION AND ENVIRONMENTAL RELATIONSHIPS OF PERMAFROST[1]

R.J.E. Brown[2]

Permafrost, or perennially frozen ground, is a term used to describe the thermal condition of earth materials, such as soil and rock, when their temperature remains below 32°F continuously for more than one year. Ice may be present. It includes ground that freezes in one winter and remains frozen through the following summer and into the next winter. This is the minimum limit for the duration of permafrost; it may be only a few inches thick. At the other end of the scale, permafrost is thousands of years old and hundreds of feet thick. The mode of formation of such old and thick permafrost is identical to that of permafrost only one year old and a few inches thick. In the case of the former, even a small negative heat imbalance at the ground surface each year results in a thin layer being added annually to the permafrost. After several thousands of years

Defn

Characteristics

Age

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How Formed

have elapsed, this process repeated annually can produce a layer of permafrost hundreds of feet thick. Above the permafrost is a surface layer of soil or rock, called the active layer, which thaws in summer and freezes in winter. Its thickness depends on the same climatic and terrain features that affect the permafrost.

Zonation of Permafrost

One-half of Canada's land surface is underlain by permafrost. The permafrost region is divided into two zones - discontinuous in the south, where permafrost exists in combination with areas of thawed ground, and continuous in the north, where permafrost occurs everywhere beneath the land surface. In the discontinuous zone, frozen and unfrozen layers exist together. In the southern fringe of this zone, permafrost occurs in scattered islands a few square feet to several acres in size and is confined to certain types of terrain, mainly peatlands. Other occurrences are associated either with the north-facing slopes of east-west oriented valleys, or with isolated patches in forested stream banks, apparently in combination with increased shading from summer thawing and reduced snow cover. Northward it becomes increasingly widespread in a greater variety of terrain types. Permafrost varies in thickness from a few inches or feet at the southern limit to about 200 feet (up to 400-500 feet in mountainous regions) at the boundary of the continuous zone,

3 zones

areas

with unfrozen layers sometimes occurring between layers of permafrost. The depth to the permafrost table ranges from about two feet to ten feet or more depending on local climatic and surface conditions. The active layer does not extend everywhere to the permafrost table. The temperature of the permafrost in the discontinuous zone at the depth of zero annual amplitude generally ranges from a few tenths of a degree below 32°F at the southern limit to about 23°F at the boundary of the continuous zone.

In the continuous zone, permafrost exists everywhere beneath the ground surface except in newly deposited unconsolidated sediments where the climate has just begun to impose its influence on the ground thermal regime. The thickness of permafrost is about 200 feet at the southern limit of the continuous zone increasing steadily to 2,000-3,000 feet in the northern reaches of the Arctic Archipelago. The active layer generally varies in thickness from about 1 1/2 to 3 feet and usually extends to the permafrost table. The temperature of the permafrost in this zone at the depth of zero annual amplitude ranges from about 23°F in the south to about 5°F in the extreme north.

In mountainous regions, such as the Western Cordillera, the distribution of permafrost varies with altitude as well as latitude. The lower altitudinal limit of permafrost decreases

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progressively from south to north. In the southern part of the Cordillera the lower limit has been estimated to decrease steadily from an elevation of about 7,000 feet above sea level at the forty-ninth parallel to about 4,000 in northern British Columbia. With increasing elevation, the distribution of permafrost changes progressively from scattered islands to widespread and, finally continuous. In amountainous regions there is the added problem of the differences between slopes of different orientation. Permafrost is more widespread and thicker on north-facing slopes than on south facing slopes. Variations in snow cover on different slopes also complicates the situation.

Environmental Factors

Climate

Climate is a basic factor in the formation and existence of permafrost. Observations indicate a broad relation between mean annual air and ground temperatures in permafrost regions. Snow cover is prominent along with the complex energy exchange regime at the ground surface causing the mean annual ground temperature, measured at the depth of zero annual amplitude, to be several degrees warmer than the mean annual air temperature. A value of 6°F can be used as an average figure but differences ranging from 2 to 10 degrees have been observed.

Present knowledge of the southern limit of permafrost indicates that it coincides roughtly with the 30°F mean annual air isotherm. Southward, permafrost occurrences are rare and small in size because the climate is too warm. Between the 30°F and 25°F mean annual air isotherms, permafrost is restricted mainly to the drier portions of peatlands and peat bogs because of the special insulating properties of peat. Scattered bodies of permafrost also occur on some north-facing slopes and in some heavily shaded areas. In the vicinity of the 25°F mean annual air isotherm the difference of 6°F between the mean annual air and ground temperature produces a mean annual ground temperature of a fraction of a degree below 32°F in most types of terrain. From the 25°F mean annual air isotherm, northward to the continuous zone, permafrost becomes increasingly widespread and thicker, and the mean annual ground temperature decreases.

Although field information is limited on the location of the boundary between the discontinuous and continuous permafrost zones in Canada, it appears to lie in the vicinity of the location of the 17°F mean annual air isotherm to correspond approximately with a mean annual ground temperature of 23°F. Field observations along the coast of Hudson Bay in Ontario and Manitoba indicate a narrow band of continuous permafrost south of the 17°F mean

annual air isotherm. From this isotherm northward, permafrost is continuous and increasingly thicker, and the mean annual ground temperature decreases.

Over a long period of time, a change in the climate represented by a change in the mean annual air temperature can result in a significant change in the extent and thickness of permafrost. Geothermal gradients ranging from about 1°F/40 feet to 1°F/300 feet - depending to some degree on the type of soil or rock - have been observed in permafrost regions in the northern hemisphere. A change of 1°F in the mean annual air temperature, for example, would result, over a long period of time, in a change of 1°F in the mean annual ground temperature. This would cause a change in permafrost thickness of approximately 40 to 300 feet.

Terrain

Terrain factors that affect permafrost conditions include relief, vegetation, hydrology, snow cover, fire, glacier ice, and soil and rock type.

(a) Relief

Relief influences the amount of solar radiation received by the ground surface and the accumulation of snow. The

influence of orientation and degree of slope is particularly evident in mountainous regions. In the discontinuous zone, this may result in permafrost that occurs on north-facing slopes but not on adjacent south-facing slopes. In the continuous zone, permafrost is thicker and the active layer thinner on north-facing slopes. Variations in snowfall and accumulation on the ground may modify these patterns. Slope and exposure (aspect) influence the vegetation, which, in turn, affects the active layer. Smaller scale variations in relief cause similar situations elsewhere in the permafrost region. Permafrost may occur, for example, in the north-facing bank of even a small stream but not in the opposite south-facing bank. Similar differences can occur even in areas of intensive microrelief, such as peat mounds and peat plateaus.

(b) Vegetation

Vegetation affects permafrost in various ways, and it is one of the more obvious indicators of subsurface conditions. It plays a much more important role in the discontinuous zone than in the continuous zone, especially in the high Arctic where it has little influence in the polar desert. The most obvious effect of vegetation is its role of shielding the permafrost from solar heat during the summer period. This insulating property is one of the most important factors

determining the thickness of the active layer. Removal or even disturbance of the surface cover causes degradation of the underlying permafrost. In the discontinuous zone, this may result in the disappearance of bodies of permafrost, while in the continuous zone, the permafrost table will be lowered. The predominance of moss and peat in protecting the permafrost from atmospheric heat is demonstrated by the fact that little change occurs in the depth of the permafrost table when trees and brush are removed, provided that the moss and peat are not disturbed.

The occurrence of permafrost in peatlands in the southern part of the discontinuous zone appears to be related to changes in the thermal conductivity of the peat through the year. During the summer the surface layers of peat become dry through evaporation. The thermal conductivity of the peat is low and warming of the underlying soil is impeded. The lower peat layers gradually thaw downward and become wet as the ice layers in the seasonally frozen layer melt. In the autumn there tends to be more moisture in the surface layers of the peat because of a decreased evaporation rate. When it freezes the thermal conductivity of the peat is increased considerably. Thus the peat offers less resistance to the cooling of the underlying soil in winter than to the warming of it in summer. As

a result, the mean annual ground temperature under peat will be lower than under adjacent areas without peat. When conditions under the peat are such that the ground temperature remains below 32°F throughout the year, permafrost results and is maintained as long as the thermal conditions leading to this lower temperature persist.

Although the influence of the ground vegetation on permafrost is dominant, trees are important. They shade the ground from solar radiation and intercept some of the snowfall in winter. The effect of even a single tree in shading the ground in summer and reducing the snowcover at its base in winter appears to influence the heat exchange at the ground surface sufficiently. The density and height of trees influence the microclimatic effects of ground surface wind velocities. Investigations in temperature regions indicate that the nature of peatland surfaces contributes to air temperatures being several degrees lower than over other natural adjacent surfaces. It is quite probable that the same situation prevails in permafrost regions.

(c) Hydrology

Water greatly influences the distribution and thermal regime of permafrost. In the discontinuous zone, the existence of permafrost is inhibited in poorly drained areas.

Precipitation influences the depth of thaw and soil temperatures. First, the amount of moisture in the soil immediately before it freezes in the autumn determines the ice content and depth of thaw the following summer; second, the moisture content of the soil surface and the infiltration of atmospheric water influence the heat transfer to the frozen soil during the thaw period. Moving water is an effective erosive agent of perennially frozen soils. There is almost always an unfrozen layer of ground under water bodies that do not freeze to the bottom. The extent of this thawed zone varies with a large number of factors - area and depth of the water body, water temperature, thickness of winter ice and snow cover, general hydrology, and composition and history of accumulation of bottom sediments. The ocean has an important thermal influence on permafrost causing it to be thinner at the shore than inland. The distribution of submarine permafrost is also greatly affected by the ocean.

(d) Snow Cover

Snowcover influences the heat transfer between the air and the ground and, hence, affects the distribution of permafrost. The snowfall regime and the length of time that snow lies on the ground are critical factors. A heavy fall of snow in the autumn and early winter inhibits winter frost penetration. On the other hand, a thick snowcover that persists

on the ground in the spring delays thawing of the underlying ground. The relation between these two situations determines the net effect of snowcover on the ground thermal regime.

In the discontinuous zone it can be a critical factor in the formation and existence of permafrost. For example, the thickest permafrost in the southern fringe of the permafrost region occurs in palsas on which snowcover is thin because of their exposure to wind. In the continuous zone, snowcover influences the thickness of the active layer. Snow has the effect of temporarily lowering near-surface ground temperatures in the active layer when it falls in summer. In the Canadian Arctic Archipelago, the effect of the snowcover is considerably diminished from its influence further south in the permafrost region because of the lower snowfall, higher density, and very uneven distribution due to drifting.

(e) Fire — with more p[illegible] + more haz[illegible] fire is going to be more [illegible]

Fire is a transient factor that is not normally considered as affecting the permafrost. Although the time of actual burning at any given point is usually of short duration, a forest or tundra fire can have a marked influence on the ground thermal regime. Many fires started by lightning occur every year in the permafrost region, particularly the discontinuous zone, which is mostly forested. Through the years much, if not

all, of this part of the permafrost region has been burned over more than once. Tundra fires are not as common because of the wet ground conditions and low proportion of woody material in the vegetation complex. Fires occur frequently, however, in the spruce-lichen woodlands of the forest-tundra transition where the thick dry continuous lichen may burn or smoulder for many months during the summer.

The degree of influence of a fire on the permafrost depends on the condition of the vegetation and the rate of burning. A fire may move rapidly through an area burning trees, charring only the top surface of the ground vegetation, and causing little change to the underlying permafrost. If dry conditions have prevailed in an area for some time prior to a fire, considerable change in the permafrost may occur in areas of ice laden perennially frozen soils due to the removal of the surface vegetation and underlying peat. Water released from melting ground ice may cause extensive erosion, landslides may occur, and a general increase in the thickness of the active layer will take place.

(f) Glacier Ice

The growth and regime of glaciers and ice caps is determined by climate, but ice is considered as a terrain factor because - like vegetation, water and snow - it forms a

layer on the ground surface between the permafrost and the atmosphere that affects the heat exchange between them. It has been postulated by many workers that the bottom temperature beneath much of a continental ice sheet is colder than 32°F. In temperate glacier conditions, the ice bottom temperature is at the pressure melting point. Beneath an ice sheet 3,000 feet thick, for example, the temperature of the water film at the bottom of the ice would be about 31.5°F. In polar glacier conditions, the bottom of the ice is frozen to the underlying ground and the temperature at the ice-ground interface is colder than 32°F. Both of these glacier conditions probably occur extensively throughout an ice sheet. Consequently, beneath Pleistocene continental ice sheets in the northern hemisphere, permafrost was probably widespread but thin because of the proximity of bottom temperatures to 32°F. Permafrost may have been somewhat thicker beneath the ice masses where the effect of cold air temperatures could penetrate to the underlying ground.

After the ice retreated, permafrost in areas covered by postglacial inundations dissipated and did not re-form until these bodies of water receded several thousand years later. In contrast with areas covered by ice sheets, much colder

temperatures were imposed by the periglacial climate on ice-free areas, producing thicker and colder permafrost than that existing beneath the ice.

Thus, continental glaciation has undoubtedly exerted great influence on permafrost conditions from one region to another. It is notable that ice sheets were much more extensive in the western hemisphere than the eastern hemisphere. All of Canada, excluding the western Yukon Territory and possibly the northwest part of the Arctic Archipelago, was covered with ice sheets during the Pleistocene. In contrast, a large part of central and eastern Siberia was not covered and here continuous permafrost now extends more than 500 miles south of the treeline, and the thickest permafrost in the northern hemisphere has been recorded.

(g) Soil and Rock Type

Bare soil and rock have considerable influence on the temperature of the ground because of their ability to reflect solar radiation. Reflectivity values in the range of 12 to 15 per cent for rock and 15 to 30 per cent for bare soil have been observed. There will also be different evaporation rates and intakes of precipitation. Variations in thermal

properties such as conductivity, diffusivity, and specific heat affect the rate of permafrost accumulation and the thickness of the active layer. The thermal conductivity of silt, for example, is about one-half that of coarse-grained soils and several times less than that of rock. These factors assume their greatest significance in the continuous zone where the climate is sufficiently cool to produce permafrost regardless of the type of terrain.

Conclusion

Fluctuations have occurred through time in the extent, thickness, and temperature of the permafrost in response to changes in climate and terrain. Since its initial formation, the permafrost in any area may have dissipated and re-formed several times during periods of climatic warming and cooling. Glacial history has had a marked effect. Changes in vegetation caused by fire, climatic succession, encroachment in water basins, or by the permafrost itself all have pronounced local effects. The regime of the fall and accumulation of snow influences the ground thermal regime. The geothermal gradient also affects the ground thermal regime. It varies in different types of soil and rock, with changes in geological structure and with time.

Thus, the environment in which permafrost exists is a complex dynamic system, the product of past and present climate and terrain features, which are in turn influenced by the permafrost. The thermal sensitivity of permafrost is such that even small changes in climate and/or terrain will produce changes in the extent, thickness, and temperature of the permafrost. The interactions of permafrost and these factors in the North are varied and very complex. Even a slight change in one factor produces a change in one or several other factors.

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